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THE HUGONIOT OF 4340 STEEL RC 54-55

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September 1979

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
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The Hugoniot of 4340 steel of Rockwell "C" hardness 54-55 has been measured. The α or b.c.c. phase Hugoniot can be represented by the equation $U = 4.67 + 1.44\,u$ where U is the wave velocity and u is the particle velocity in km/s. The Hugoniot of the ε or h.c.p. phase above the 13GPa transition point is close to that of rolled homogeneous armor.

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I. INTRODUCTION

For some time the Ballistic Research Laboratory has been measuring and studying the mechanical and physical properties of materials of interest to the Army. This includes a spectrum of tests from slowly applied loads in convential testing machines to shock loading with light-gas gun impacts or high explosives. This report gives results of shock wave tests on 4340 steel of Rockwell "C" hardness 54-55. It, also, includes ultrasonic and quasi-static data which provide zero points on the high pressure Hugoniot curves. Table I gives a chemical analysis of this material.

Like iron and rolled homogeneous armor (RHA), 4340 steel displays a phase transition under shock loading at approximately 13 GPa. This causes the material to display a one, two, or three wave structure depending on the initial shock strength. Hauver[1,2] has discussed this phenomenon in two recent reports on the Hugoniot of RHA. The experimental method used for this study is the same as Hauver's and consists of measuring and analyzing the free surface motion of a sample of material shocked in the usual one-dimensional strain experiment. This motion can become complicated when the three wave structure is encountered. The analysis used is the same as in the aforementioned reports. It is based on a mid-point of the wave analysis used by Barker[3], in which the wave velocities are measured from the half amplitude points in the wave.

II. EXPERIMENTAL

The experimental specimens were cut out of a 100mm (4-inch) round bar of material and heat-treated to RC 54-55 hardness. They were, then, machined to final dimensions. The heat-treatment consisted of soaking at 860°C for 30 minutes, oil quenching, drawing down at 315°C for 1 hour, and air cooling. The measured density of the material was 7800 kg/m^3.

The experiments were performed with the BRL light-gas gun. The free surface motion was measured with a laser velocity interferometer called a VISAR which was developed by Barker[4]. Figure 1 shows the results of five tests performed at different impact velocities. Four are symmetrical impacts of nominal 6.13mm thick plates of 4340 steel 76mm in diameter and

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[1] *G. Hauver, "The Alpha-Phase Hugoniot of Rolled Homogeneous Armor", Ballistic Research Laboratory Memorandum Report No. 2651, August 1976.*

[2] *G. Hauver and A. Melani, "The Epsilon-Phase Hugoniot of Rolled Homogeneous Armor", Memorandum Report ARBRL-MR-02909, March 1979.*

[3] *L. M. Barker, "Alpha-Phase Hugoniot of Iron", J. Appl. Phys., Vol. 46, No. 6, June 1975, pp 2544-7.*

[4] *L. M. Barker and R. E. Hollenbach, "Laser Interferometer for Measuring High Velocities of Any Reflecting Surface", J. Appl. Phys., Vol. 43, No. 11, November 1972, pp 4669-75.*

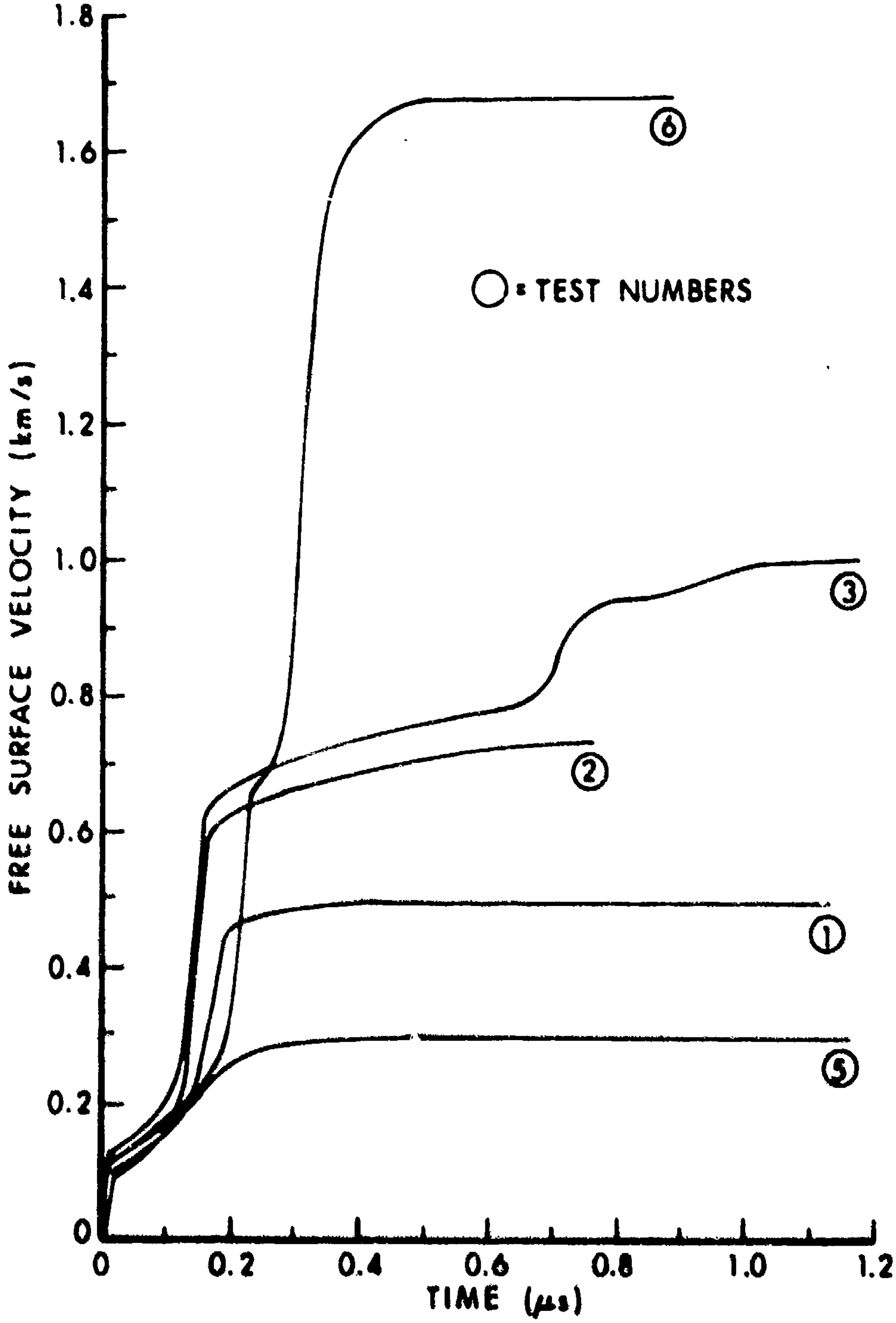

FIGURE 1: VISAR Results for 5 Tests with 4340 Steel

one (Test #6) is the result of the impact of a 3.0mm thick tungsten plate on a 9.43mm thick 4340 steel specimen.

The elastic wave velocity was measured using an ultrasonic device constructed by Hauver[1] and called by him "The Thumper". This velocity, which was used in subsequent data analysis, was 5.86 km/s.

The low pressure α-phase goes through the bulk sound velocity at the zero point. This velocity has been calculated from bulk modulus measurements made in quasi-static compression tests in which the volumetric change with load was measured. This was accomplished by measuring both the axial and circumferential strains using resistance strain gages applied directly to circular cylindrical specimens. The volumetric strain was then calculated from equation (1)

$$\frac{\Delta V}{V_o} = (1+\epsilon_a)(1+\epsilon_c)^2 - 1 , \qquad (1)$$

where,

ϵ_A = axial strain

ϵ_c = circumferential strain.

Since in a uniaxial strain experiment the pressure is one-third of the axial stress, the slope of the curve shown in Figure 2 is the bulk modulus. The calculated bulk sound velocity is then 4.67 km/s. Poisson's ratio was also directly calculated using the axial and circumferential strain measurements.

III. RESULTS

Table II shows in tabular form the Hugoniot points deduced from the data and one point measured in an experiment by Hauver in which both RHA and 4340 were shocked to high pressure with an explosively thrown steel plate. For the α or b.c.c. phase the shock velocity-particle velocity line is represented by the least squares equation U = 4.67 + 1.44 u where U is the shock velocity and u the particle velocity. The α to ε or h.c.p. phase transition occurred at an average shock pressure of 13.2 GPa. The average dynamic elastic limit was 2.41 GPa. The measured Poisson's ratio was 0.288. This gives, according to Jones and Graham[5] a hydrostatic transition pressure of 12.2 GPa.

[5] O. E. Jones and R. A. Graham, "Shear Strength Effects on Phase Transition "Pressures" Determined from Shock-Compression Experiments", *Symposium on the Accurate Characterization of the High Pressure Environment*, U.S. Dept. of Commerce, National Bureau of Standards, Gaithersburg, MD., October 14-18, 1968.

The elastic limit measurements varied widely as did measurements by Butcher and Canon[6] on this material. It is surprising and encouraging that their average value was the same, 2.41 GPa.

Figures 3 and 4 show the U-u plots for 4340 RC 54-55 steel compared to both RHA and iron. It can be seen that the α-phase of each material has practically the same slope but the intercept depends on the bulk sound velocity. The ε-phase of RHA and 4340 are the same within the experimental error.

ACKNOWLEDGEMENTS

The authors would like to thank George Hauver for his help with the experiments and especially for his explanations of the data analysis. We would like to thank R. Benck and D. Diberardo for the quasi-static measurements.

TABLE I

CHEMICAL ANALYSIS OF 4340 STEEL

ELEMENT	RESULTS %
Carbon	0.40; 0.39
Manganese	0.69
Phosphorus	0.005
Sulfur	0.014
Silicon	0.26
Nickel	1.65
Copper	0.15 - 0.25
Chromium	0.7 - 0.9
Vanadium	0.01
Molybdenum	0.2 - 0.3
Aluminum	0.02

*Dept of Army Materials Laboratory, Frankford Arsenal, 16 September 1976.

[6] *B. M. Butcher and J. R. Canon, "Influence of Work-Hardening on the Dynamic Stress-Strain Curves of 4340 Steel",* AIAA J., *Vol. 2, No. 12, December 1964, pp 2174-9.*

TABLE II
HUGONIOT DATA
α - phase

$\rho_o = 7800\ kg/M^3$
$= 7.80\ gm/c.c.$

TEST NO.	U km/sec	u km/sec	σ_ϵ GPa	σ_{P1} GPa	σ_1 GPa
1	5.03	0.255	2.29	8.11	10.40
2	5.13	0.319	2.06	11.05	13.11 (α+ϵ)
3	5.12	0.320	2.74	10.49	13.23 (α+ϵ)
5	4.98	0.155	2.63	3.79	
6	5.11	0.320	2.33	10.81	13.14 (α+ϵ)
			ave 2.41		ave (α+ϵ) 13.16

ϵ - phase

	U	u	σ_2
3	2.97	0.498	17.67
6	4.69	0.840	33.39
SC554*	7.60	2.25	133.60

*Hauver

Key

U - shock velocity
u - particle velocity
σ_ϵ - dynamic elastic limit
σ_{P1} - α-phase stress
σ_1 - total stress in first plastic wave
σ_2 - total stress in second plastic wave
ρ_o - density

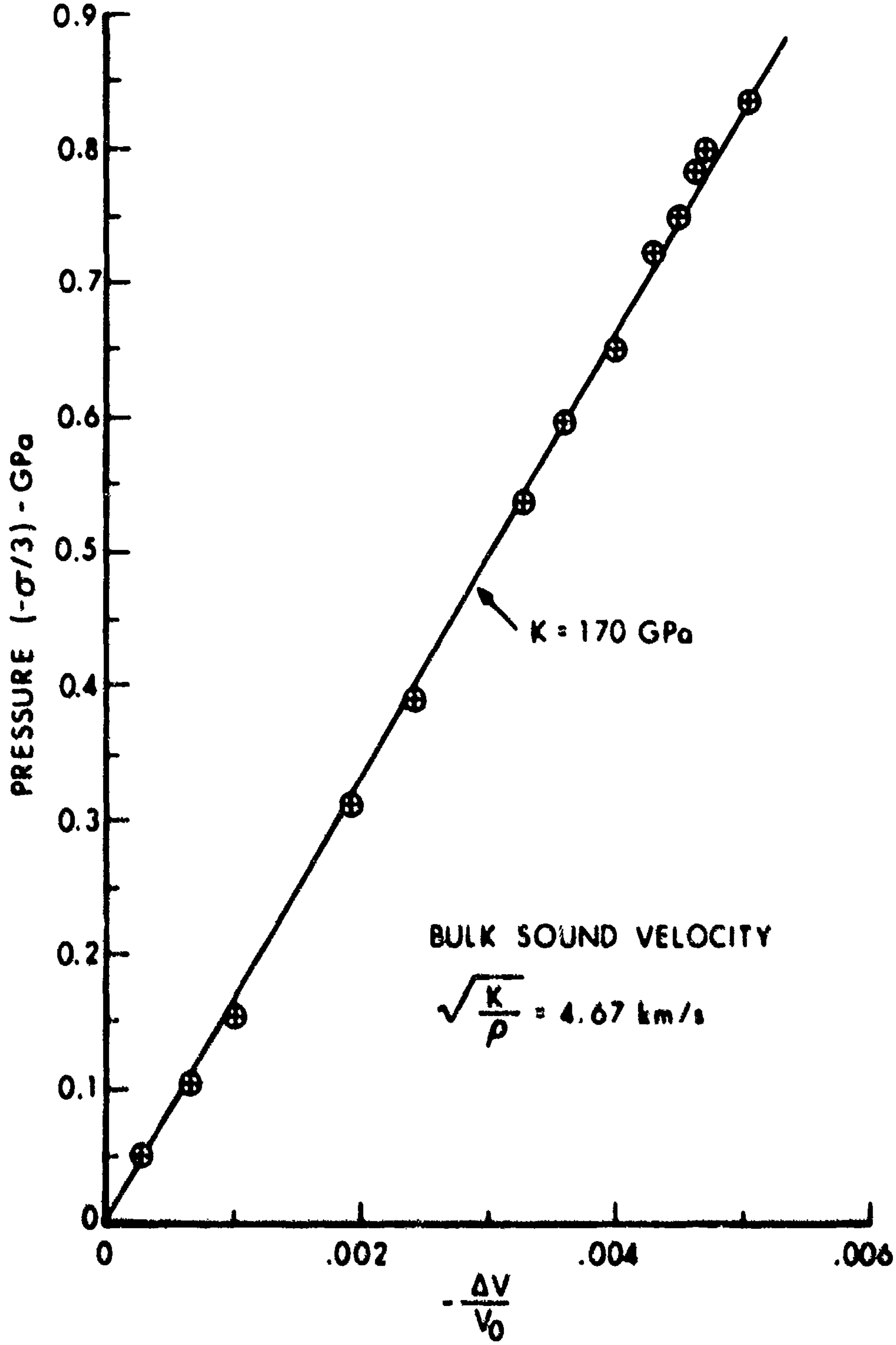

FIGURE 2: Pressure vs. Volume Compression for 4340 Steel. The pressure is taken as $-\sigma/3$ where σ is the load divided by the original area of the specimens.

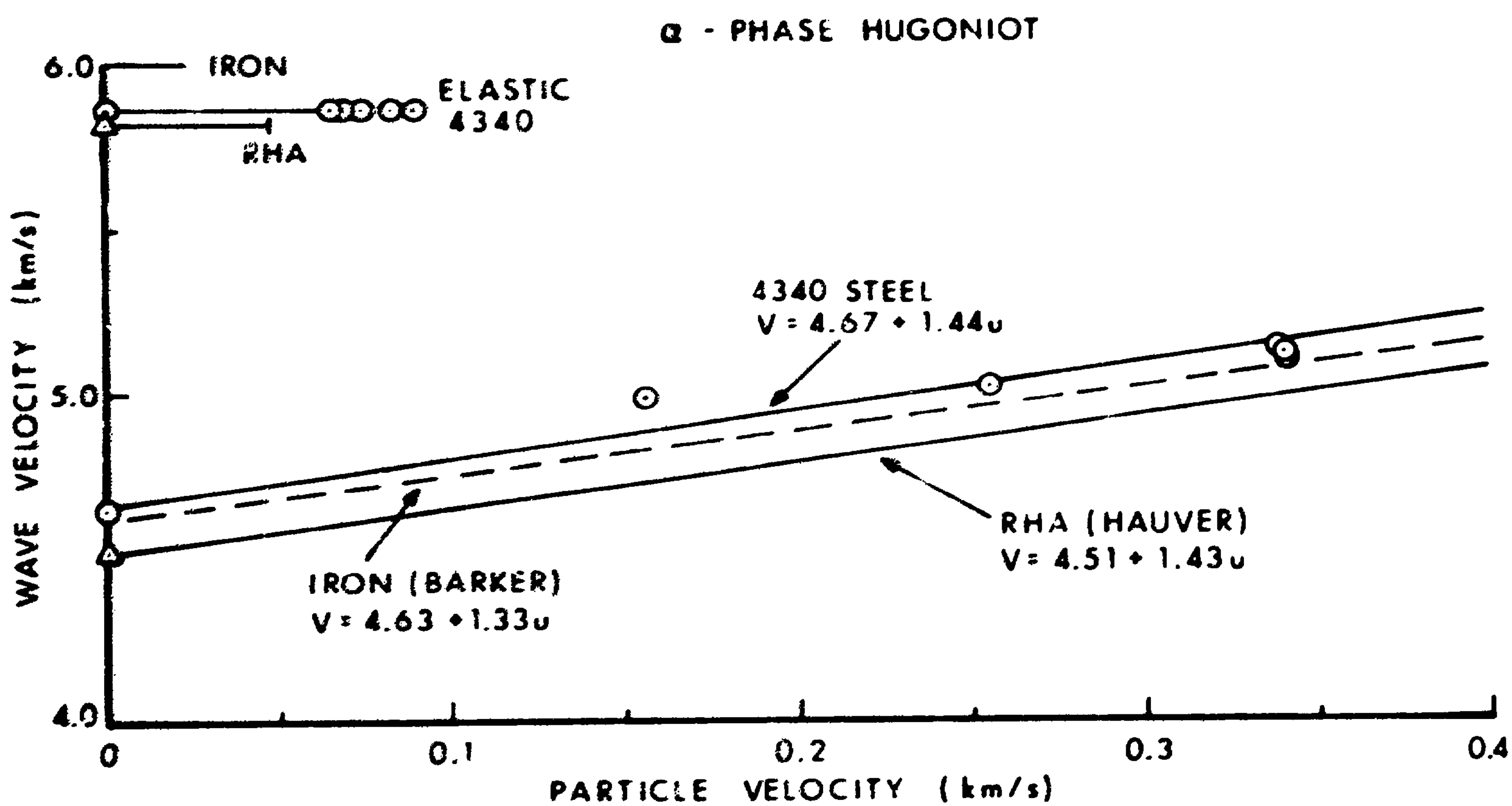

FIGURE 3: Comparison of α-Phase Hugoniot Results for Iron, 4340 Steel, and RHA.

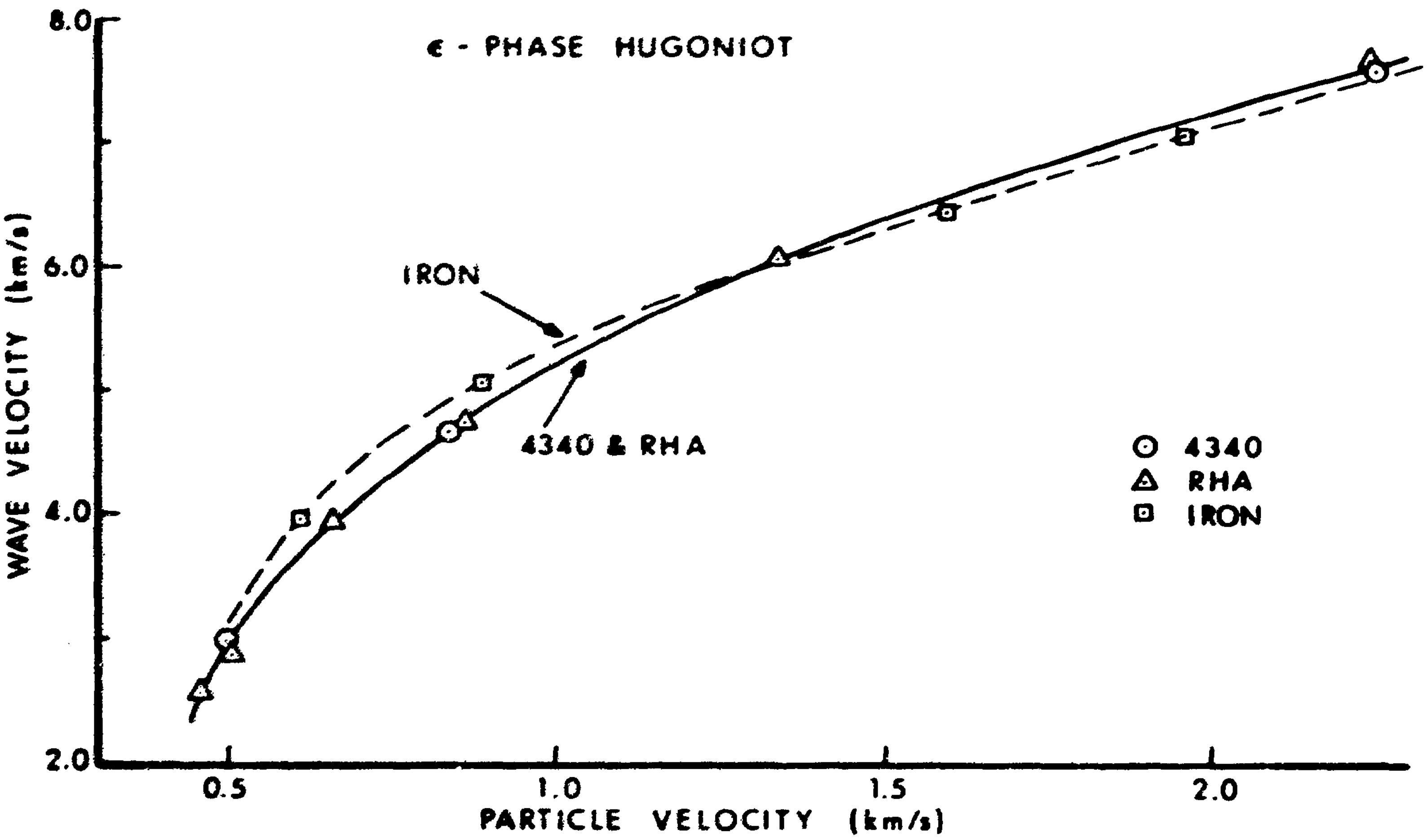

FIGURE 4: Comparison of ϵ-Phase Hugoniot Results for Iron, 4340 Steel, and RHA.

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3. L. M. Barker, "Alpha-Phase Hugoniot of Iron", J. Appl. Phys., Vol. 46, No. 6, June 1975, pp 2544-7.

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5. O. E. Jones and R. A. Graham, "Shear Strength Effects on Phase Transition "Pressures" Determined from Shock-Compression Experiments", Symposium on the Accurate Characterization of the High Pressure Environment, U.S. Dept. of Commerce, National Bureau of Standards, Gaithersburg, MD., October 14-18, 1968.

6. B. M. Butcher and J. R. Canon, "Influence of Work-Hardening on the Dynamic Stress-Strain Curves of 4340 Steel", AIAA J., Vol. 2, No. 12, December 1964, pp 2174-9.

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